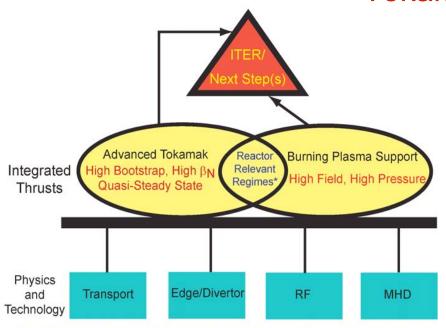


#### Plasma-wall interaction studies of the Alcator C-Mod Tokamak



\*Equilibrated electrons-ions, no core momentum/particle sources, RF  $\rm I_p$  drive

Sandia PFC meeting December 6, 2004

Presented by B. Lipschultz on behalf of the C-Mod Team

#### Outline

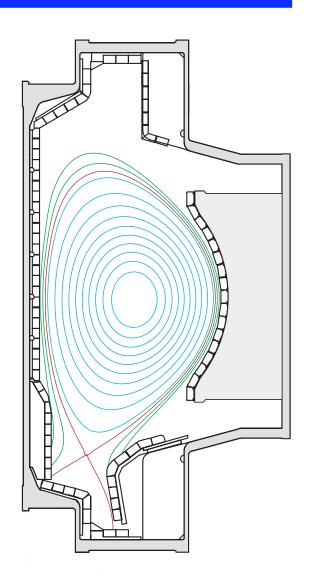


- General description
- Conditioning
- Molybdenum sources
- Mo erosion and D retention studies
- Dust
- Melting of Mo
- W-brush tile development
- New Lower Hybrid Current Drive
- Summary

## Alcator C-Mod

### Alcator C-Mod: Compact, High Field

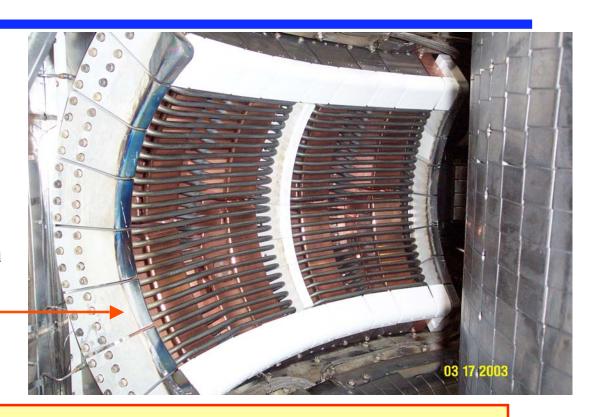
- Toroidal Magnetic Field = 2 to 8 Tesla
- R = 0.67 m, a = 0.21 m
- Plasma Volume = 1 m<sup>3</sup>
- Plasma Current to 2.0 MA
- Temperature: 1 to 6 keV
- Density: 10<sup>20</sup> to 10<sup>21</sup> m<sup>-3</sup>
- All RF driven, no Neutral Beam heating
- State of the art diagnostics
- Metal plasma-facing components (Mo)
  - Experimenting with other materials



## Alcator C-Mod

### All RF Auxiliary Heating, CD

- Ion Cyclotron Heating (ICRF)
- 8 MW Source
  - 4MW @80 MHZ
  - BN protection tiles
  - High power density!
- 2 dipole, 1 four-strap antenna
- Four-strap phaseable for heating or current drive



- Heating
  - H minority at 5.4 Tesla (80 MHz on-axis)
  - <sup>3</sup>He minority at 8 Tesla
  - Mode conversion (direct e<sup>-</sup> heating)
- Current drive (Fast Wave and Mode Conversion)



#### Wall materials and wall conditioning

- Walls are stainless steel, tiles generally molybdenum.
  - We have operated with antenna limiters made of BN
- After a vacuum break
  - Bake @ ~ 130°C to reduce water (and H levels which affect the ICRF absorption) for 10 days.
  - Electron-Cyclotron discharge cleaning (ECDC) to clean walls
  - Discharges to lower the H/D level further
- Every day
  - 2 hours of ECDC prior to run
  - Walls at room temperature





#### Boronization on Alcator C-Mod

- Typically deposit 5 g of boron during a boronization
  - 10% B<sub>2</sub>D<sub>6</sub> in 90% helium
  - 12 hours of electron cyclotron discharge to deposit the B
  - 100 nm deposition
- Boronize again after approximately 200 discharges after
  - Moly radiation increases
  - H/(H+D) ratio increases and affects ICRF heating
- Currently testing an idea for boronizing during plasma discharges - a 'salt shaker' which drops ~ 50 μm size B grains into the plasma.

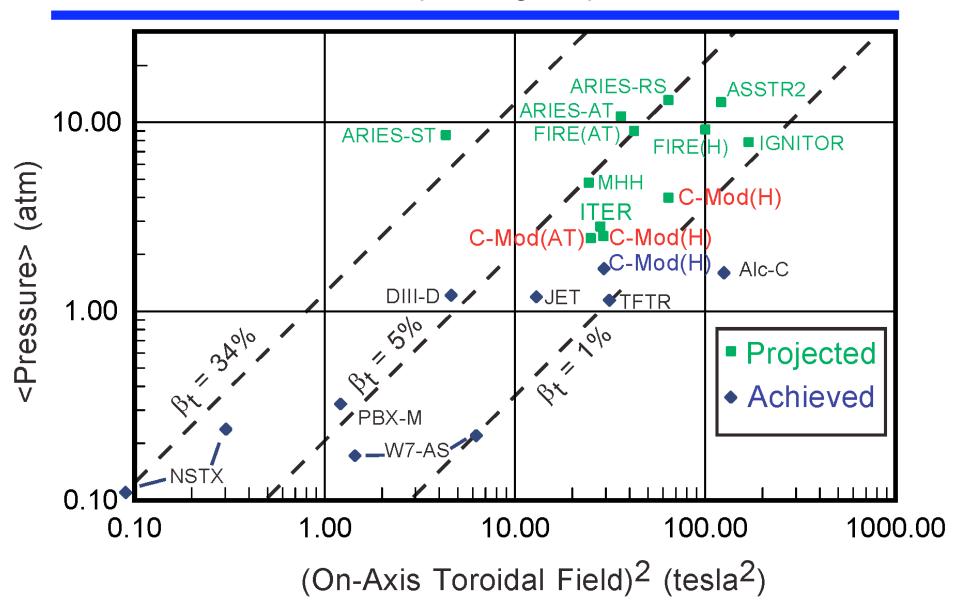


### **Unique C-Mod Capabilities**

- Unique dimensional parameters (B/R, Power/Area, Plasma Pressure)
  - Key data determining empirical scaling of plasma performance
  - Key data for testing of basic physics understanding
    - Dimensionless Identity experiments (neutrals, radiation, ...)
    - Pedestal structure and regulation
- Equilibrated electrons and ions like a reactor (due to high density)
- ITER-level SOL power density, metal Plasma Facing Components
  - Reactor relevant divertor heat flux regime (~1GW/m² parallel power density)
  - Unique recycling properties, D/T retention
- Reactor-like normalized neutral mean free path (depends on B<sub>poloidal</sub>)
- Prototypical disruption forces
  - ITER level plasma pressure, energy density (disruption mitigation)
- Exclusively RF driven (also reactor-prototypical)
  - Heating decoupled from particle, momentum and current sources
  - Efficient off-axis current drive with Lower Hybrid
- Long pulse relative to skin and L/R times (test of current drive and profile control)

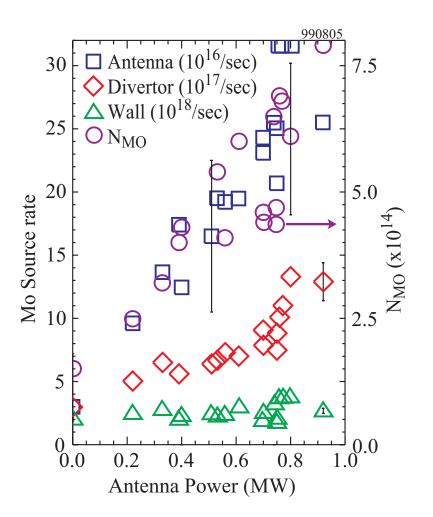


## C-Mod should reach ITER pressure at same $\beta$ Power reactors require higher pressure





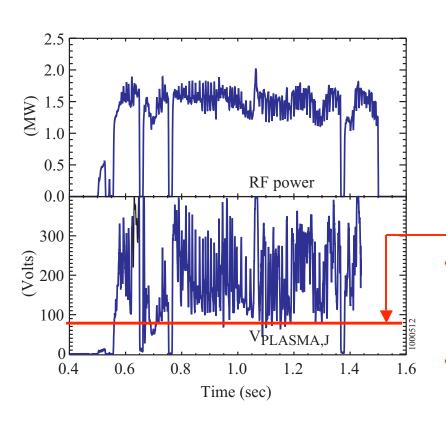
#### Mo source linked to RF effect



- Mo sources monitored
  - Antenna, inner wall, divertor
- Close correlation of core Mo with antenna source
- Antenna far out in SOL
  - Sources should be small
  - RF sheath rectification appears to be responsible
  - High probability of sputtered Mo entering the core from outer edge



#### RF sheath rectification effect can be dealt with



- When the RF is on
  - Electrical loop formed connecting antenna to wall to limiter and back thru plasma
  - Electrons can react to RF frequency but ions cannot
  - High sheath potential forms accelerating ions into surfaces at
     energies > sputtering threshold
- Mo tiles changed to. BN on antennas
  - Sheath rectification reduced
  - Antenna Mo source eliminated
- New campaign will start with a retry of Mo antenna tiles with reduced RF fields

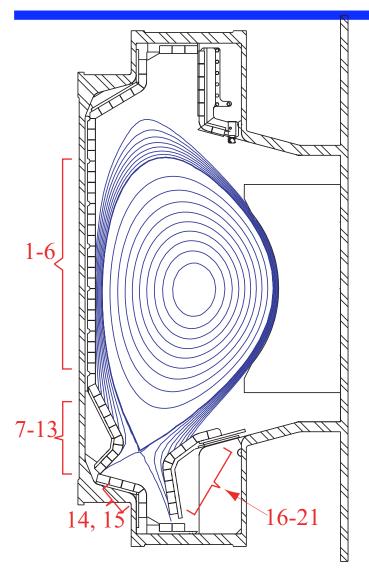


#### Mo erosion and D retention

- Most detailed work on Mo erosion and H/D content in several papers/reports
  - W. Wampler et al., JNM 266-269 (1999) 217., W. Wampler et al., SOFE-99
    - Utilized markers on a series of tiles to determine erosion over run period
    - Surface analysis also provided the D and B densities
  - D. Pappas et al., JNM 266-269 (1999), D. Pappas, PhD thesis MIT report PSFC-RR-00-6.
    - Measured Mo influx rate spectroscopically
    - Modeled outer divertor erosion (sputtering) & redeposition
    - Model compared influx rates (and net ersosion) w/Wampler results
- I will review the above results and show some melting information

# Wampler study utilized markers at a number of poloidal locations

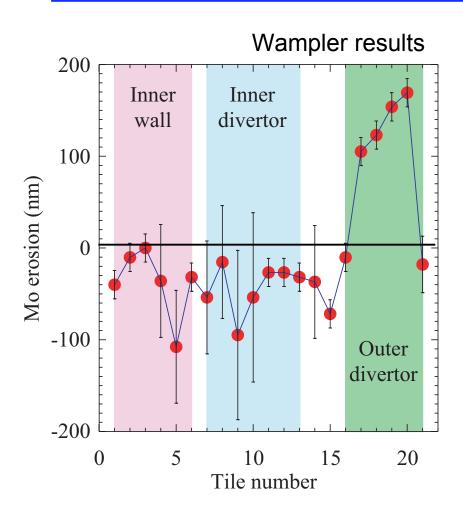




- Cr marker layer 100 nm thick
- Mo overlayer 300-600 nm (measured for each tile before installation)
- All on top of standard Mo tiles

### Mo erosion highest at outer divertor

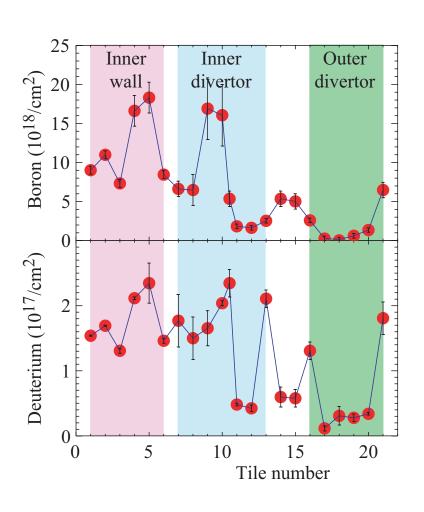




- Erosion concentrated at outer divertor
  - Inner divertor typically detached
  - Net erosion highest away from strike point region
  - Local redeposition can be ~ 90%
- Model of erosion/redeposition (Pappas)
  - Based on divertor probe measurements
  - Primarily B<sup>+2</sup> physical sputtering
  - Consistent with net erosion (within x2-3)
- Net erosion ~ 0.14 nm/s (0.45 cm/exposure-year)
  - ~ 20x smaller than a similar study w/carbon tiles (Whyte, DIII-D)

# Boronization leads to B layers and D retention

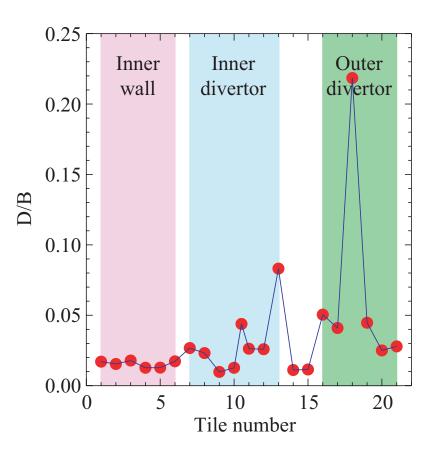




- B erosion similar to Mo (outer divertor) occurring fairly quickly (20-40 discharges)
- B deposition appears to be at inner wall & divertor, as well as PFZ.
- D levels low, particularly where B low

## D/B ratio low compared to C machines and to theoretical B limit





- D/B ratio can theoretically be of order 0.4
- In regions of thick B layers the D/B ratio is low - likely due to multiple boronizations and thin active layer (few nm).
- D/B ratio larger at outer divertor
  - uncertainties large due to very thin B layer
- Generally, only 2.5% of the retained D is in the divertor.
- Wall D inventory ~ 100x that in plasma
- Estimated T retention ~ 10 x less than for C machine
- Typical wall-fueling saturation time ~ 1 sec before and after boronization.

## Similarities and differences with low-Z PFC tokamaks



- Generally see a pattern of erosion similar to other tokamaks
  - Outer divertor erosion, deposition elsewhere
- Having a lot of B around does not seem to have changed the recycling characteristics in a major way.
- The amount of D retained in the B seems quite low compared to the maximum allowable.
  - We cannot rule out co-deposition
- The wall-fueling equilibration time is ~ 1 shot.
- Wall pumping
  - In an individual shot the amount pumped by the wall is often ~15% of what is injected.
  - Over a whole day the amount released by disruptions during the shot or (more often) during rampdown ~ equals the amount pumped during other shots.

## Alcator C-Mod

#### Dust found where expected

- Collaboration with INEEL
  - Report DAP-23-98
- Vacuum dust though .02 μm pore size Anopure filter (21 locations)
- Lift-off tape samples as well (13 locations)
- As expected the dust is primarily found on the floor

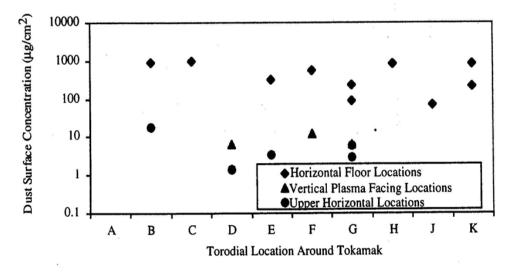


Figure 2.7 Graph of the torodial mass distribution of dust around the machine grouped into three general machine locations.

# Metal dust much different than from C PFC machines



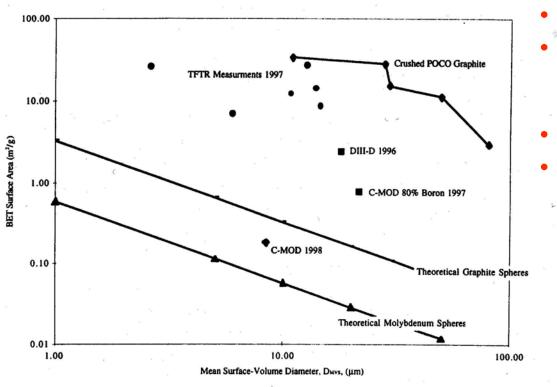


Figure 6.1. Graph of the BET Specific Surface area plotted verses the mean surface-volume diameter for a variety of materials, previous measurements, and the current C-MOD measurement.

- Mixture of Mo and steel dust
- Spherical as opposed to flakes found in other tokamaks
- Near theoretical limit
- Calculate added surface
  - Concentration 10g/m²
  - ~ 1.5 m<sup>2</sup> at vessel bottom
  - Dust surface area=0.18 m²/g
  - Added area =
     10g/m²•1.5 m² 0.18 m²/g
  - Added area ~ 3.5 m<sup>2</sup>
  - C flakes 100x larger area

# Melting primarily where surfaces misaligned

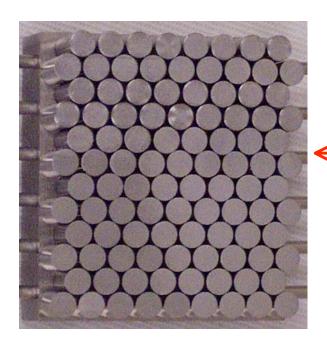




- Example shown is for a divertor plate that moved out of position due to halo current forces.
- Melting localized to edge which stuck out in front of neighboring divertor module
- We did not correlate these melted areas (on a number of modules) with changes in core Mo levels but there may have been
- Melt layer shows ripples and is mostly affected by gravity.
- Some movement toroidally

# Tungsten will make its appearance in C-Mod soon





- Important Sandia collaboration
- Tungsten welding rods (3 mm dia) used
  - Grains parallel to length
  - Inconel base
- Testing several attachment methods
- Mechanical locking of rod into base
  - Brazing of rod into inconel
- 12 tiles to be installed this month (divertor)
- Testing
  - IR views of 9 tiles, CCD camera views of 3 tiles
  - Spectroscopic views for W influx
  - Plan for maximal high heat flux at end of run period.
- Interested in leading edge and melting experience

# C-Mod experience indicates that a low-Z main chamber has advantages

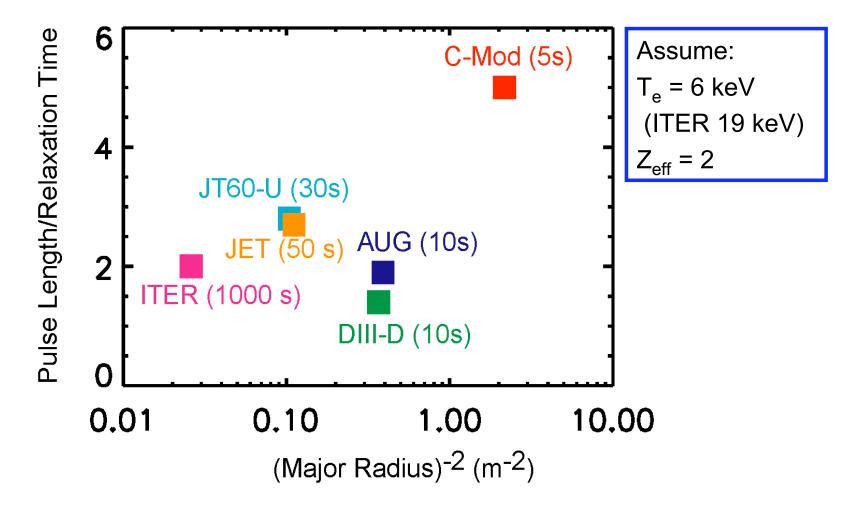


- Boronization
  - lowers Mo levels at high power even after the B is completely eroded from the outer divertor
  - Did not seem to have a significant effect on our recycling and fueling
- Antenna limiters were changed to BN because of sheath rectification issues. This also lowered the Mo injection during ICRF heating.
- Other poloidal limiters and inner wall still Mo (boronized).
  - ⇒ We have generally found that reducing the high-Z material in regions of poor impurity screening (outer edge) is important
- Dust levels are consistent with expectations, low and less flake-like than w/C
- The C-Mod experience with Mo and B indicates that the combination of the two gives:
  - Low D/T inventory
  - Low-Z impurity sources in the main chamber where the impurity screening is poor

#### Next step: Advanced Features for steady state



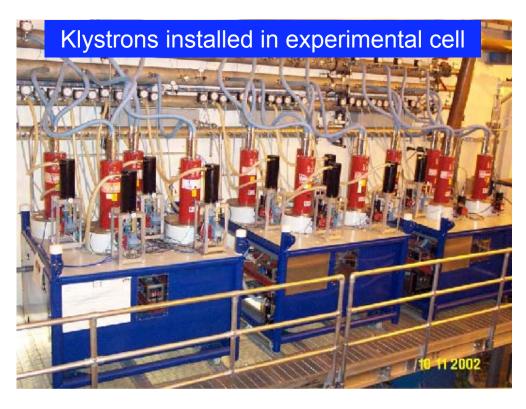
- Steady State
  - High bootstrap fraction + Efficient current drive
- C-Mod positioned to study fully relaxed current profiles

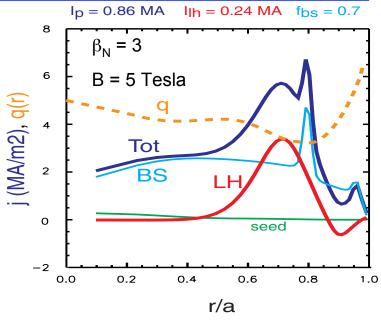


## Lower Hybrid will be used for far Off-Axis Current Drive



- LHCD (4.6 GHz, 4 MW)
  - Far off-axis
- Target plasma is fully non-inductive, at nowall limit, 70% bootstrap fraction
- First experiments: Winter 2005









# C-Mod making important contributions to tokamak PFC experience



- Developing ICRF Heating & Current Drive
- Experience with high-Z and low-Z in the same machine
  - Mo erosion and D retention studies.
  - Dust
  - Melting of Mo
- New tile development (W-brush)
- New Lower Hybrid Current Drive
- C-Mod also unique w/respect to physics studies
  - Size & field make it important in empirical scaling studies
  - Important in dimensionless parameter scaling tests of underlying plasma physics